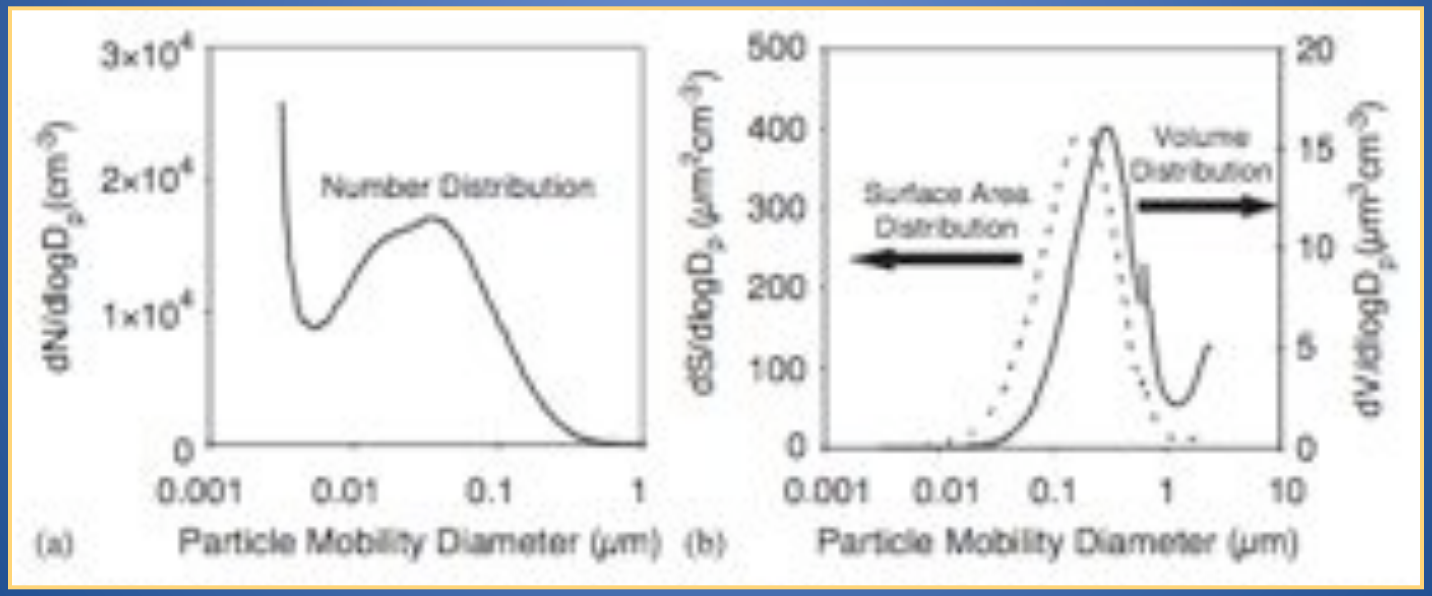
Exposure to Ultrafine Particles:
Bay Area Elementary Schools and Beijing High-rise Apartments

Nasim A. Mullen

Presentation at Lawrence Berkeley National Laboratory
September 10, 2010

Ultrafine Particles (UFP)

- Defined by diameter, $d_p \leq 0.1$ μm (lower limit undefined)
- Correlate poorly with particle mass (PM) concentration
- Correlate well with particle number (PN) concentration

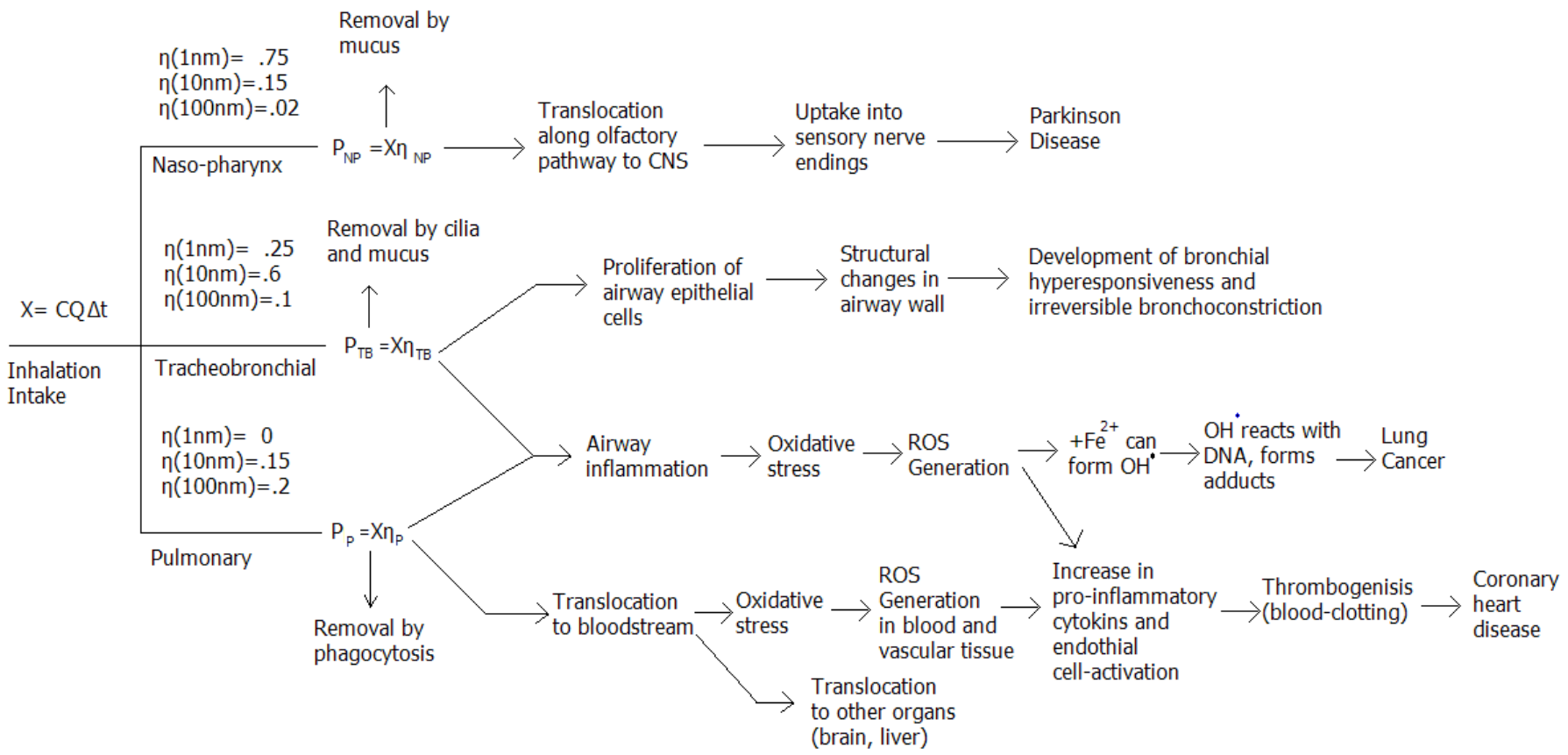


Average distribution calculated from one year of measurements in Pittsburgh, PA (Stanier et al., 2004)

UFP Exposure: Proposed Health Effects

- Daily Mortality and Fine and Ultrafine Particles in Erfurt, Germany." *Whichman et al 2000*
  - $NC_{0.01\text{-}0.1}$; RR=1.055 for 4-day lag
  - $PM_{2.5}$; RR=1.033 for 0-day lag
  - PM_{10}; RR=1.036 for 0-day lag
- RR=1.26 found for $PM_{2.5}$ by Dockery et al. (1993)

Possible Biological Pathways



CARB Study: Ultrafine Particle Concentrations in Schoolrooms and Homes

Research Team

- UC Berkeley: Nasim Mullen, Seema Bhangar, William Nazaroff
- Aerosol Dynamics Inc.: Susanne Hering, Nathan Kreisberg

Dates of Field Work

- Homes: November 2007 – August 2008
- Schools: June 2008 – December 2008

Current knowledge: Classroom IAQ and health

Student health and performance associated with…

- Elevated CO_2 (Myhrvold et al., 1996; Shendell et al., 2004; Madureira et al., 2009; van Dijken et al., 2006; Simoni et al., 2010)
- Low air-exchange rate (Wålinder et al., 1997 and 1998; Smedje & Norbäck, 2000)
- Visible mold (Koskinen et al.,1997; Simons et al., 2010)
- VOC concentration (Norbäck et al.,1990; Smedje et al., 1997)
- Airborne bacteria and mold concentration (Smedje et al.,1997)
- Elevated PM_{10} (Simoni et al., 2010)

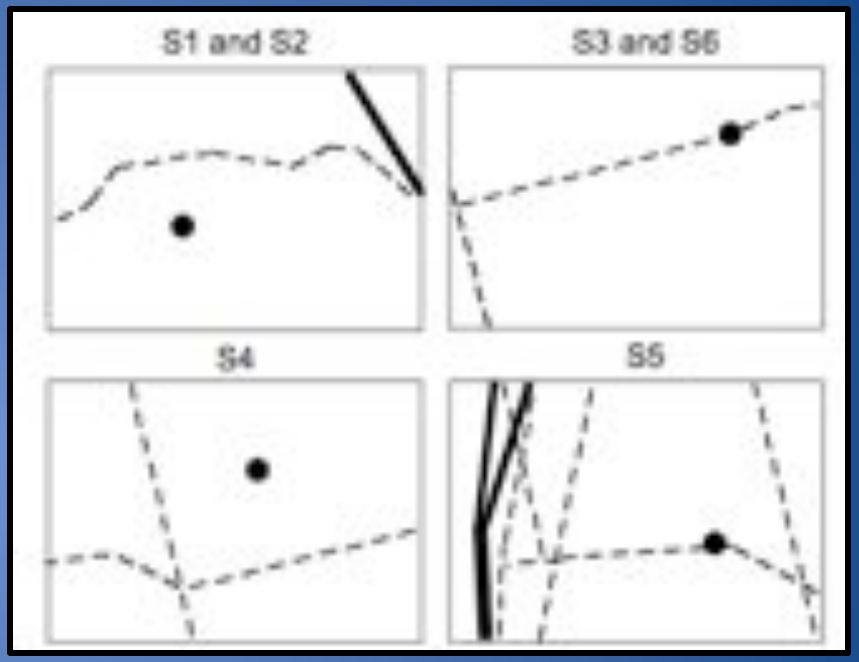
Current knowledge: Classroom UFP concentrations

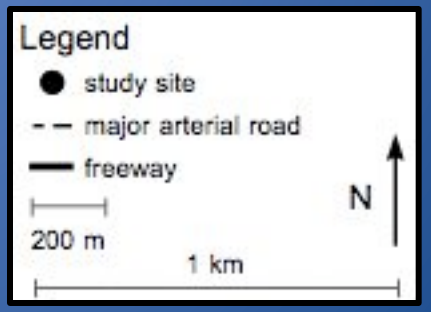
- Munich, Germany: Fromme et al. (2007), 36 classrooms. No significant indoor sources.
- Athens, Greece: Diapouli et al. (2007), 7 schools. No significant indoor sources.
- Southwest Germany: Zöllner et al. (2007), 27 schools. No significant indoor sources
- Pembroke, Ontario: Weichenthal et al. (2008), 37 classrooms. No significant indoor sources.
- Australia (small village): Guo et al. (2008), 1 classroom for 2-weeks. Indoor sources: classroom cleaning, candle burning, match/kerosene burning.
- Brisbane, Australia: Morawaska et al. (2009), 3 classrooms. Indoor sources: art activities, cleaning

Questions Investigated in Alameda County Classroom Study

- What are the classroom UFP exposure levels?
- What are the factors affecting exposure levels?
- How do classroom exposures compare to residential exposures?
- Are indoor sources important?
- Are classrooms “well-ventilated”?
- Are UFP levels influenced by changes in classroom ventilation?

Classroom Sites

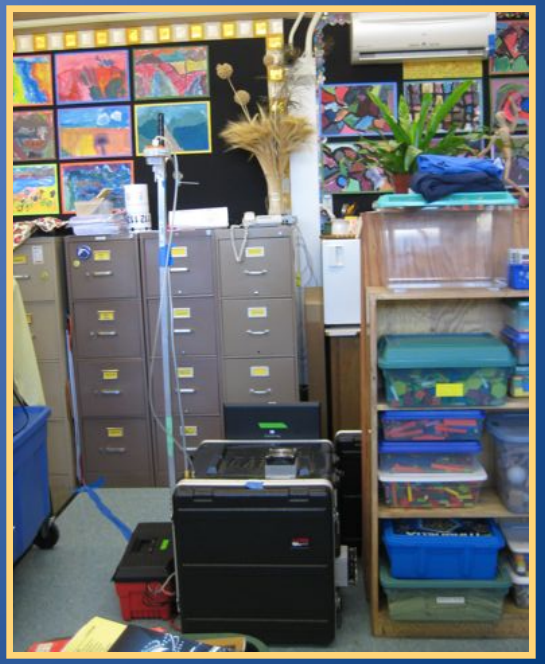




Figures by William Nazaroff

Data Collection Methods

- Water-based condensational particle counter (WCPC) used to measure UFP indoors and outdoors at 1-minute resolution
- O_3, NO, CO and CO_2 also monitored
- Researcher observation and sensors used to record occupant activities



Data Analysis Methods

- Air-Exchange Rate (λ)

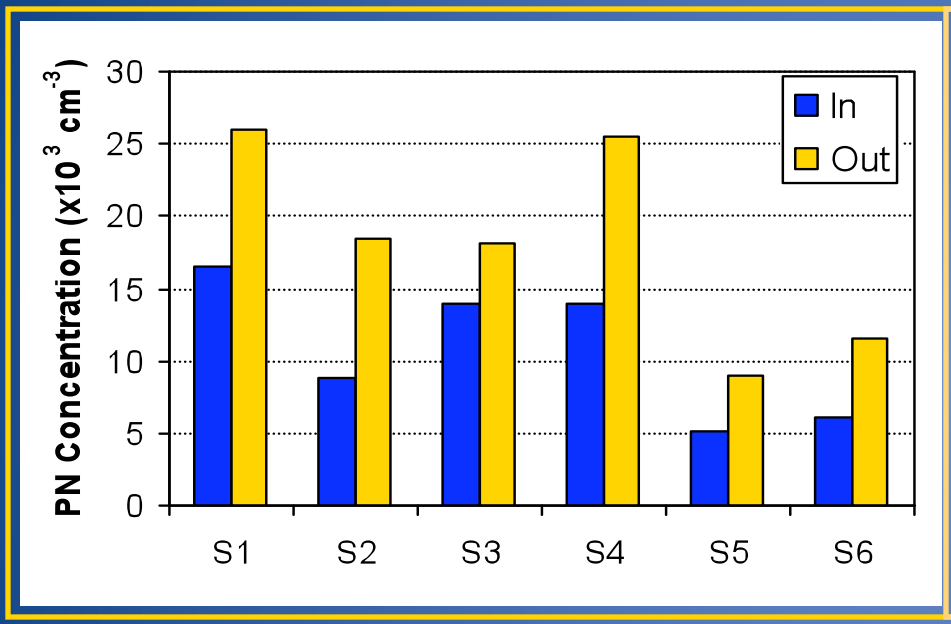
$$\frac{dY_{in}}{dt} = \frac{E(t)}{V} + \lambda \cdot Y_{out} - \lambda \cdot Y_{in} \longrightarrow \lambda = \frac{\int_{t_i}^{t_f} \frac{E(t)}{V} dt - \left(Y_{in}(t_f) - Y_{in}(t_i)\right)}{\int_{t_i}^{t_f} Y_{in}(t) dt - \int_{t_i}^{t_f} Y_{out}(t) dt}$$

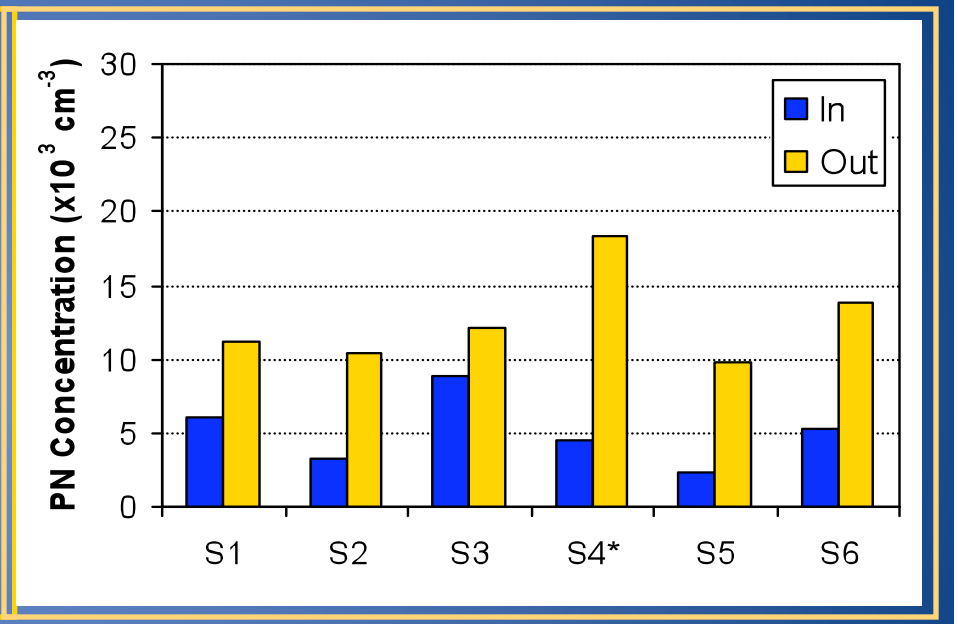
- Indoor Proportion of Outdoor Particles (f)

$$\frac{dN_{in}}{dt} = \left(f \cdot N_{out} - N_{in}\right) \cdot \left(k_d + \lambda\right) \longrightarrow f = \frac{\frac{N_{in}(t_f) - N_{in}(t_i)}{k_d + \lambda} + \int_{t_i}^{t_f} N_{in}(t)}{\int_{t_i}^{t_f} N_{out}(t)}$$

- Y_{in}, Y_{out} = Indoor and outdoor CO_2 concentration, respectively (ppm)
- N_{in}, N_{out} = Indoor and outdoor PN concentration, respectively (cm^{-3})
- E(t) = Emissions of CO_2 by occupants (cm^3/hr)
- V= Volume of the classroom (m^3)
- k_d = Deposition rate of particles indoors (h^{-1})

Results: Time-averaged PN Concentration





Occupied Periods

Vacant Periods

*Outdoor monitoring at S4 was discontinued from 12am to 6am every day

Example PN Time-Series: S1

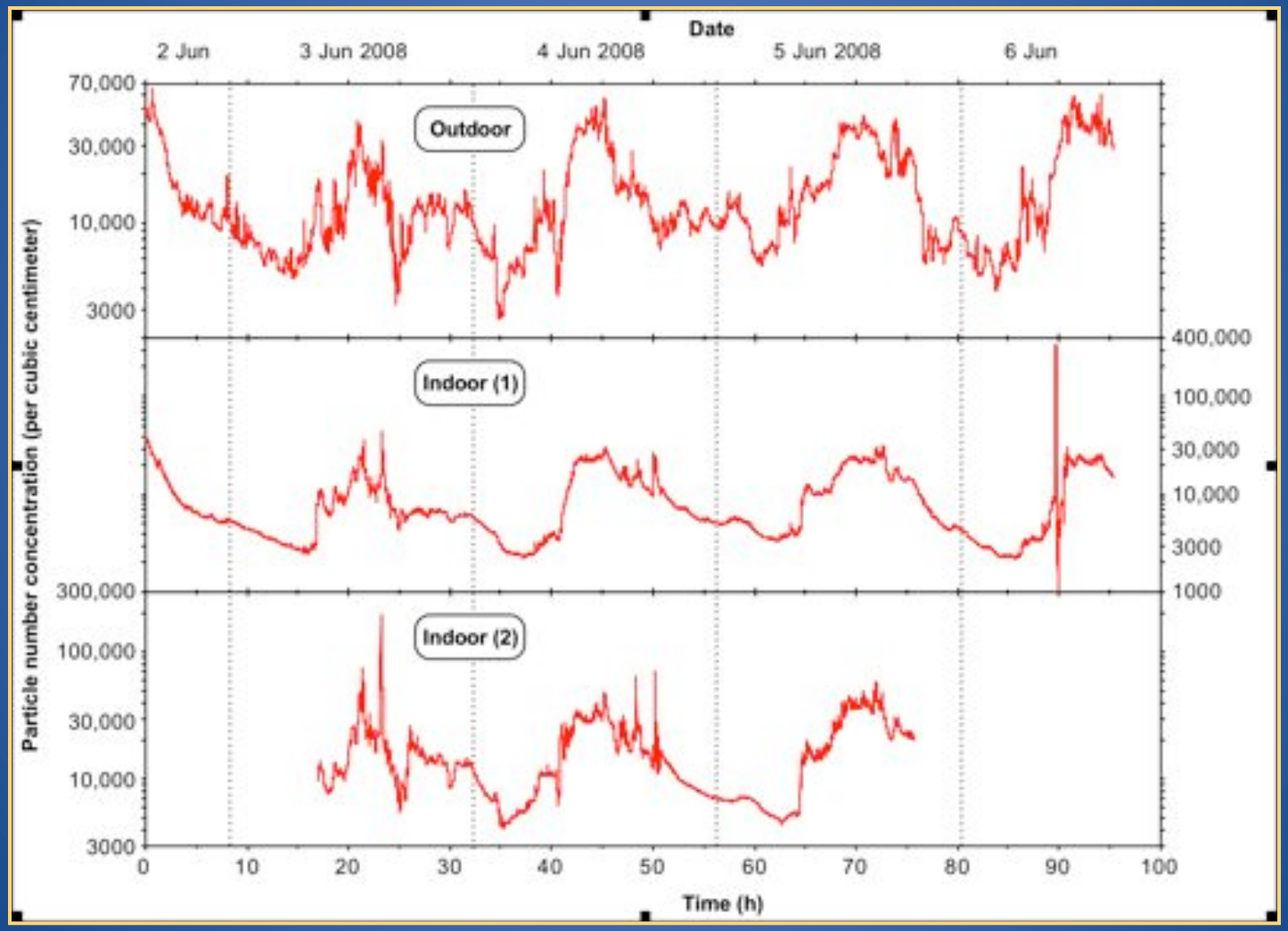


Figure created by William Nazaroff

Example PN Time-Series: S5

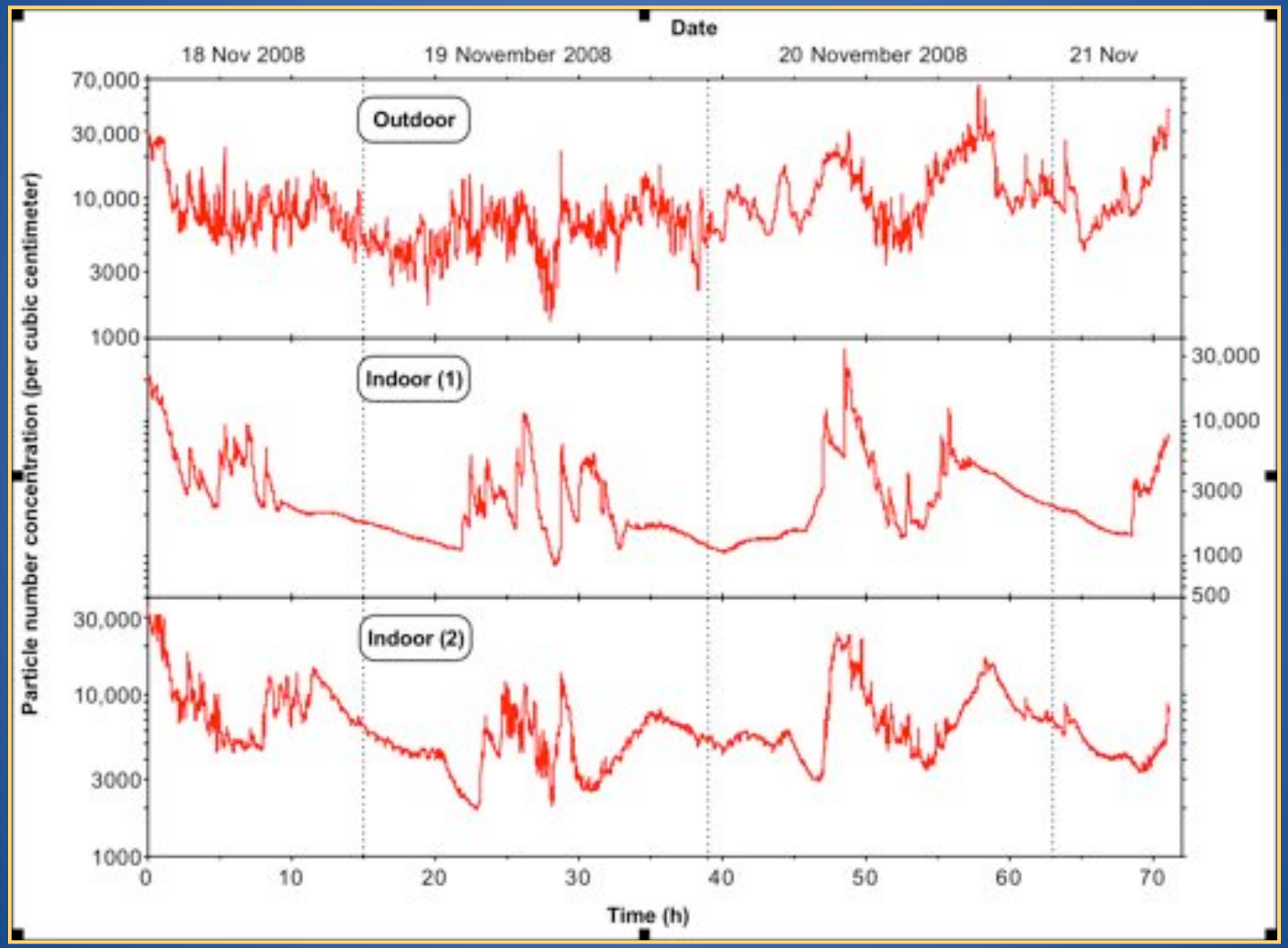
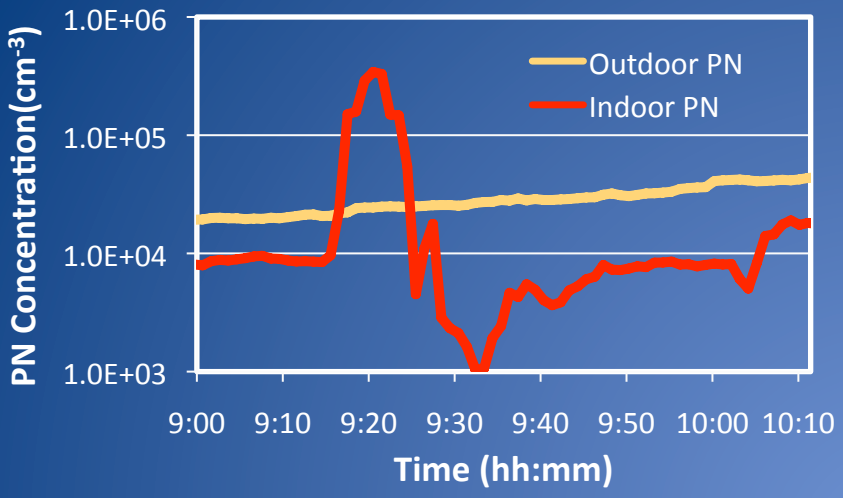
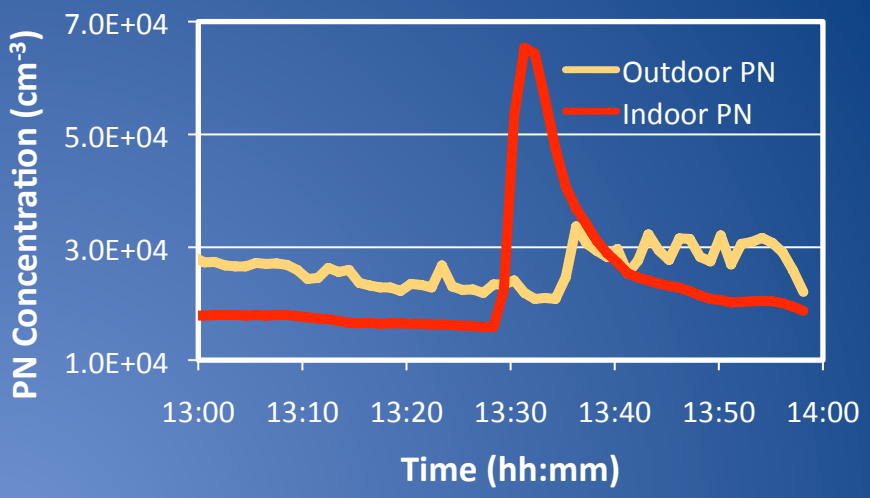


Figure created by William Nazaroff

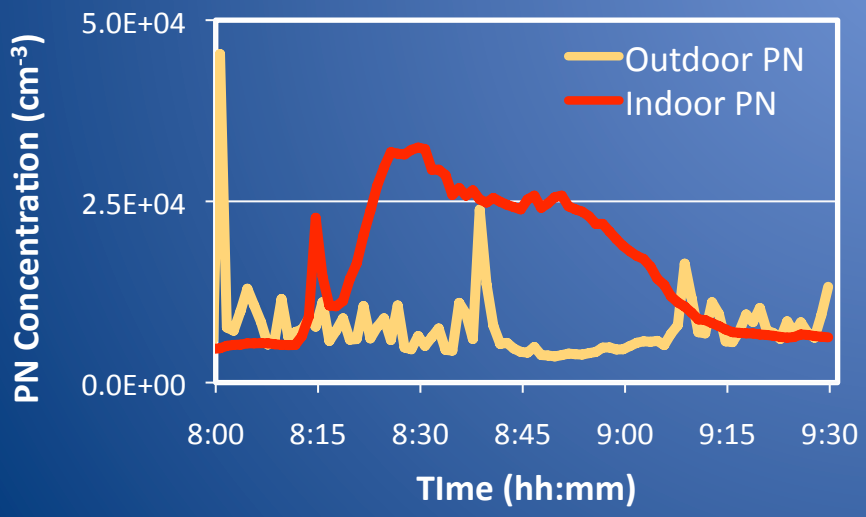
Source Events



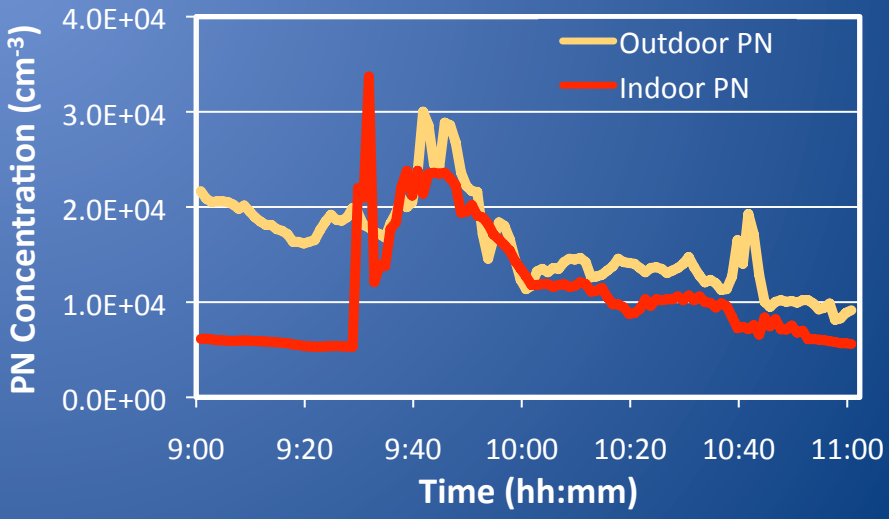
S1- Pancake cooking



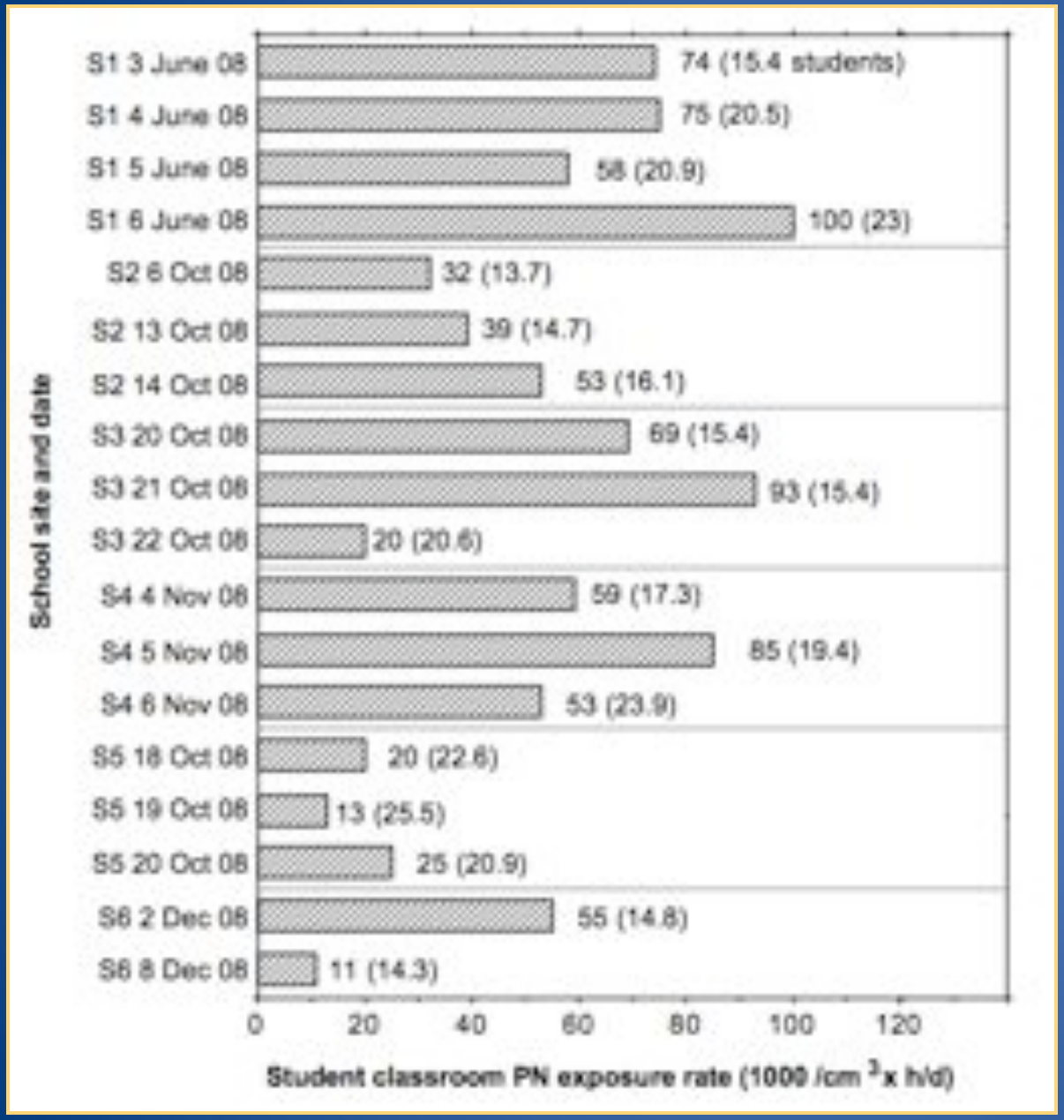
S3 - Candle



S3 - Heater



S5 - Heater



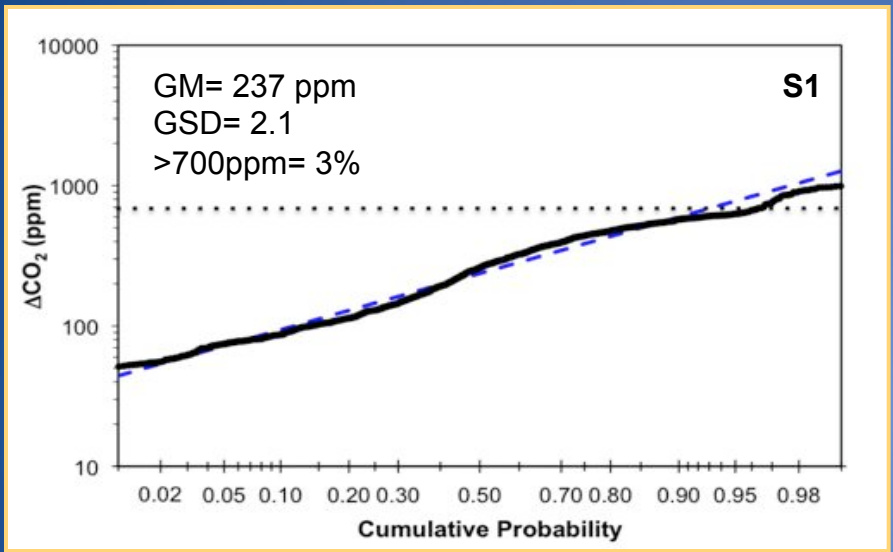
Daily Integrated Student Exposure

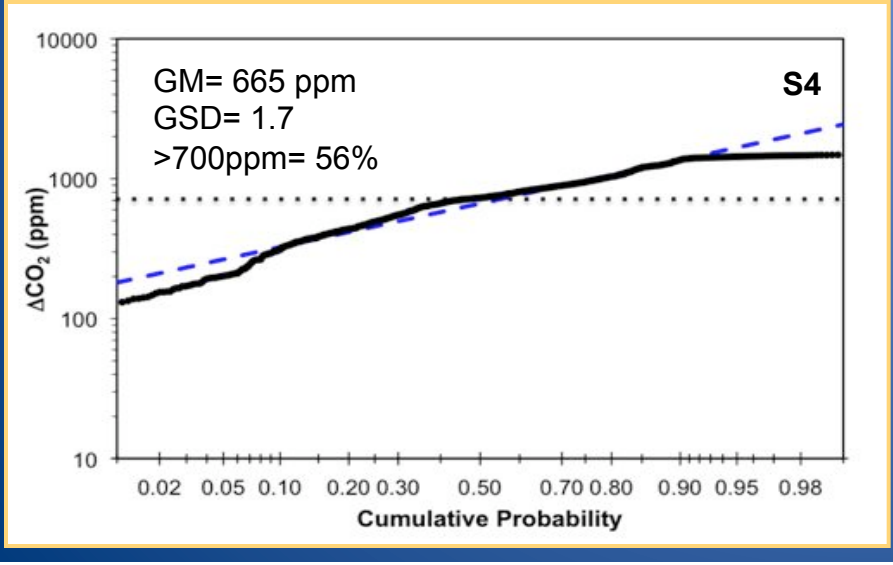
Mean in schools:
50 x 10^3 cm^{-3}• h/d
(RSD= 46%)

Mean in homes:
320 x 10^3 cm^{-3}•h/d
(RSD= 71%)

Figure by William Nazaroff

Indoor minus outdoor CO_2 when students were present





Distribution of 1-minute average $CO_{2,in} - CO_{2,out}$

Results across all sites:

- GM= 268 ppm
- GSD= 2.8
- 18% of measurements >700ppm

Ventilation per Person (VPP)

	VPP (L/s)
S1	18
S2	15
S3	99
S4	7
S5	6
S6	7

- ASHRAE standard= **5 L/s**
- EUROVEN proposal= **25 L/s**

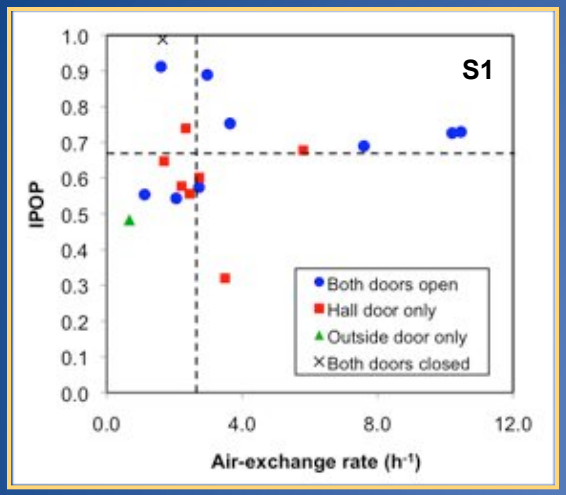
- Santamouris et al. (2008) results:
  - Median naturally-ventilated classrooms= **3 L/s** (21 papers reviewed)
  - Median mechanically-ventilated classrooms= **8 L/s** (22 papers reviewed)

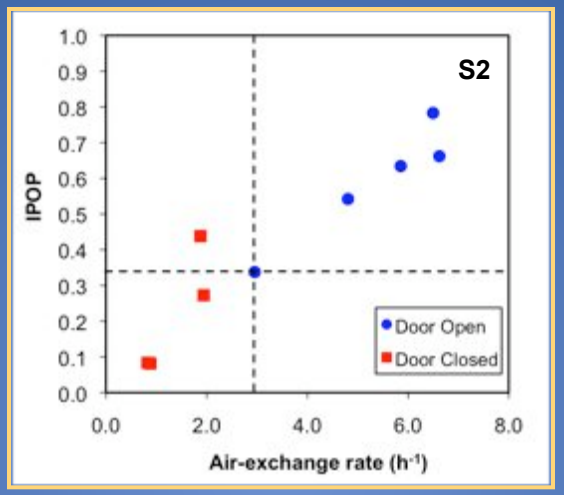
Air-Exchange Rate (**AER**) and Indoor Proportion of Outdoor Particles (**IPOP**)

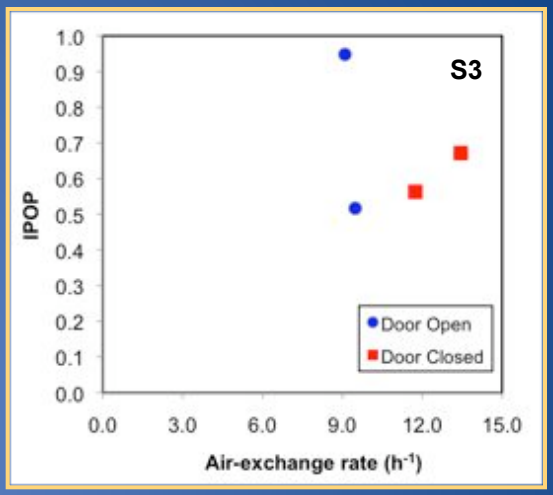
	DOOR(S) OPEN					DOOR(S) CLOSED				
	AER (h^{-1})	AER range	IPOP (-)	IPOP range	N	AER (h^{-1})	AER range	IPOP (-)	IPOP range	N
S1	3.6	0.7-10.5	0.67	0.32-0.91	17	1.7	-	0.99	-	1
S2	5.6	1.9-6.6	0.62	0.27-0.78	5	0.9	0.82-0.88	0.08	0.08-0.08	2
S3 [a]	9.3	9.1-9.5	0.72	0.52-0.95	2	12.5	11.7-13.5	0.61	0.56-0.67	2
S4	2.9	1.1-8.8	0.63	0.35-0.92	9	0.8	0.7-0.8	0.42	0.40-0.43	2
S5 [a]	1.6	1.0-2.0	0.51	0.28-0.88	4	2.5	1.1-4.8	0.43	0.24-0.57	5
S6	4.4	-	0.73	-	1	0.7	0.3-2.6	0.40	0.19-0.82	11

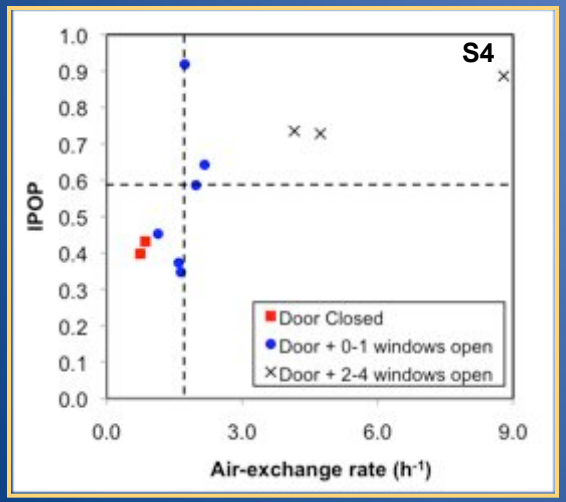
[a] S3 and S5 had continuous mechanical ventilation during hours of student occupancy

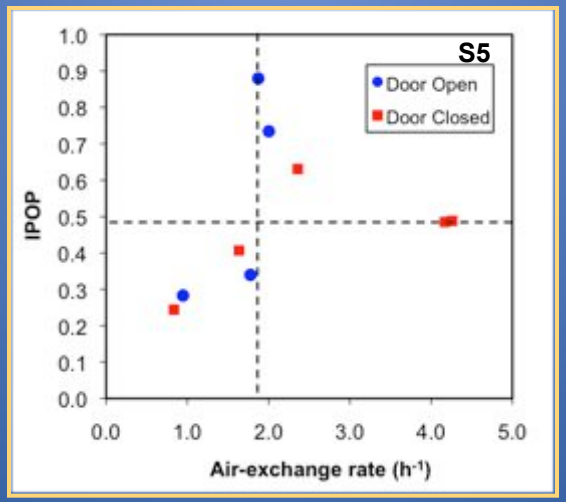
IPOP vs. AER

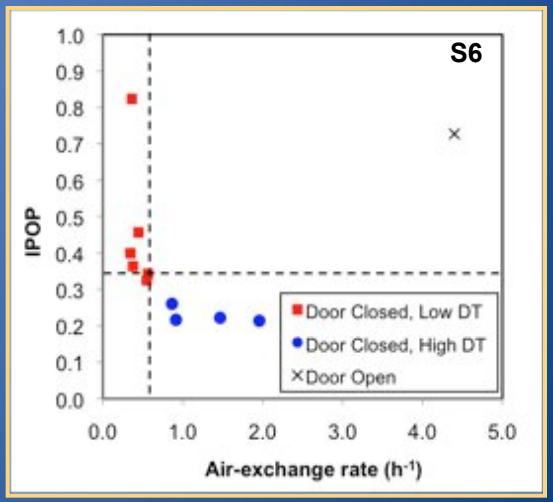

S1
IPOP
Air-exchange rate (h-1)
Both doors open
Hall door only
Outside door only
Both doors closed


S2
IPOP
Air-exchange rate (h-1)
Door Open
Door Closed


S3
IPOP
Air-exchange rate (h-1)
Door Open
Door Closed


S4
IPOP
Air-exchange rate (h-1)
Door Closed
Door + 0-1 windows open
Door + 2-4 windows open


S5
IPOP
Air-exchange rate (h-1)
Door Open
Door Closed


S6
IPOP
Air-exchange rate (h-1)
Door Closed, Low DT
Door Closed, High DT
Door Open

Alameda County Classroom UFP Exposure: Conclusions

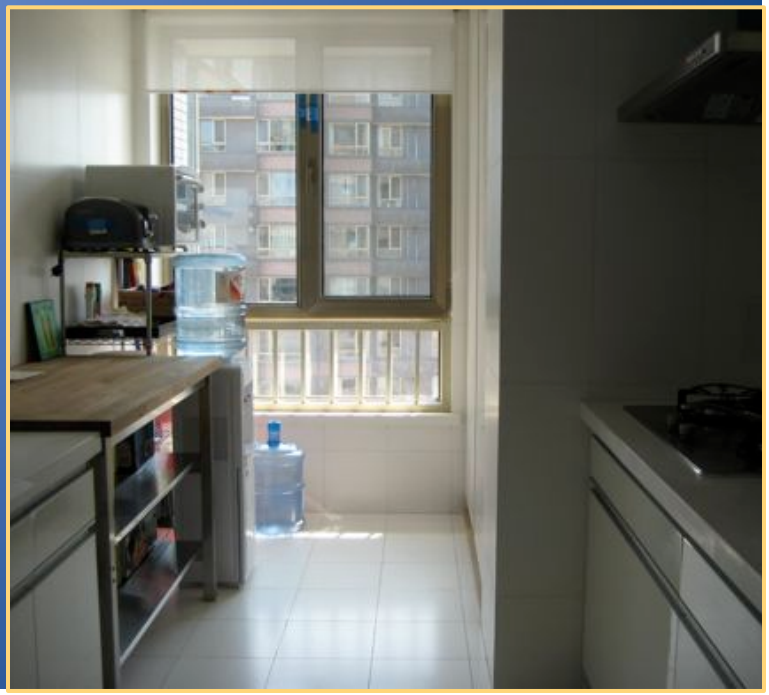
- Outdoor sources are main contributor to indoor PN
- PN concentrations are higher when the classroom is occupied compared to when it is vacant
- Exposure in classrooms is lower than in homes
- Ventilation appears adequate in the majority of classrooms
- In some cases, higher AER results in higher IPOP

Characterizing Exposure to Ultrafine Particles in Beijing High-Rise Apartments

- Dates of Field work: June - August 2009
- Chinese Collaborators: Dr. Yinping Zhang, Dr. Shuxiao Wang and Liu Cong from Tsinghua University

What is known about IAQ in urban Chinese residences?

- Ethylbenzene and xylene emissions suspected from cooking and building materials (Ohura at al., 2009)
- PAH emissions suspected from cooking, mothballs and indoor smoking (Zhu et al., 2009)
- Formaldehyde and acetaldehyde emissions suspected from building materials (Weng et al., 2010)



What is known about UFP in urban Chinese residences?

No prior studies of UFP in urban residences

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Ultrafine particle concentrations and exposures in four high-rise Beijing apartments

Nasim A. Mullen [a,*], Cong Liu [b], Yinping Zhang [b], Shuxiao Wang [c], William W. Nazaroff [a]

[a] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, USA
[b] Department of Building Science and Technology, Tsinghua University, Beijing, China
[c] Department of Environmental Engineering, Tsinghua University, Beijing, China

Characteristics of Beijing, China

- Population: 22 Million; Pop. Density ~ 1,300/ km^2
- Since 1980's, housing boom has resulted in construction of mostly high-rise buildings
- Mean outdoor PN (2004-2006)= 32,800 cm^{-3} (Wu et al., 2008)
- Mean outdoor $PM_{2.5}$ (2007)= 74–92 $\mu g/m^3$ (Zhao et al., 2009)

Research Questions

- What are the UFP exposure levels in Beijing high rise apartments?
- What proportion of exposure comes from indoor / outdoor sources?
- What are the indoor sources?
- How do results in Beijing compare to results from Alameda County?

Data Collection Methods

- Simultaneous indoor and outdoor PN measurement for 48+ continuous hours
- Monitored in 4 apartments within high rise buildings in 3 neighborhoods
- Documented occupant behavior using sensors and questionnaires

Data Analysis Methods

- Daily-Integrated PN exposure due to residential exposures (cm^{-3} x h/d):

$$\overline{Exp} = \frac{PN_{awake} h_{awake} + PN_{asleep} h_{asleep}}{d_{monitored}}$$

- PN_{awake} , PN_{asleep}= PN average during hours a given resident was awake or asleep, respectively (cm^{-3})
- h_{awake}, h_{asleep}= Hours a given resident was awake or asleep, respectively (h)
- $d_{monitored}$= Days monitored (d)

Site Characteristics

A1
- 180 m^3
- ~50 m from major roadway
- 7^{th} floor
- 2 adults

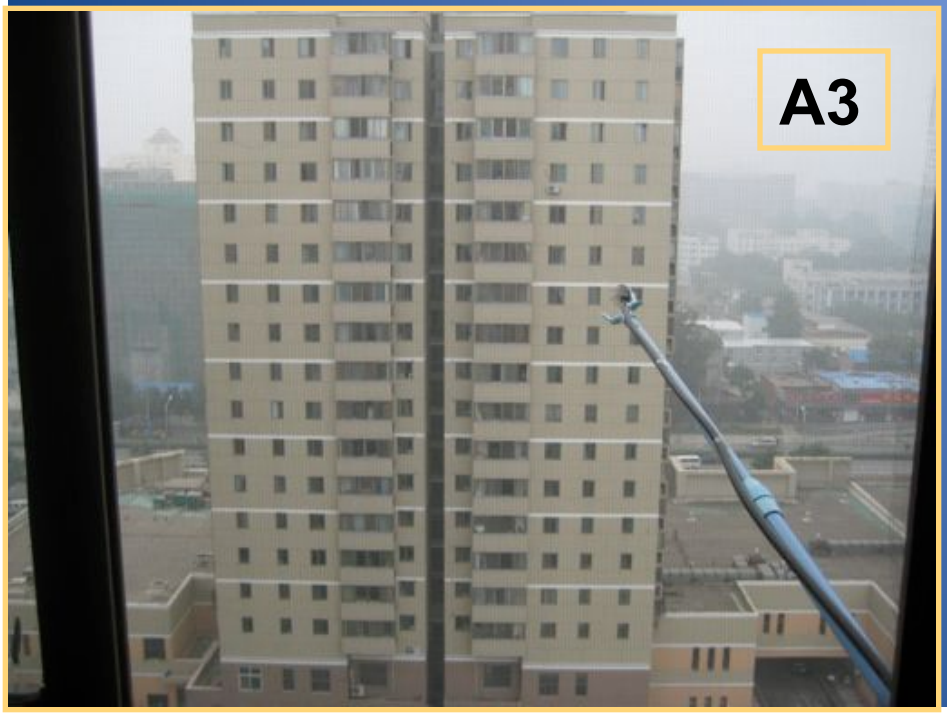
A2
- 280 m^3
- ~150 m from major roadway
- 23^{rd} floor
- 2 adults +1 child

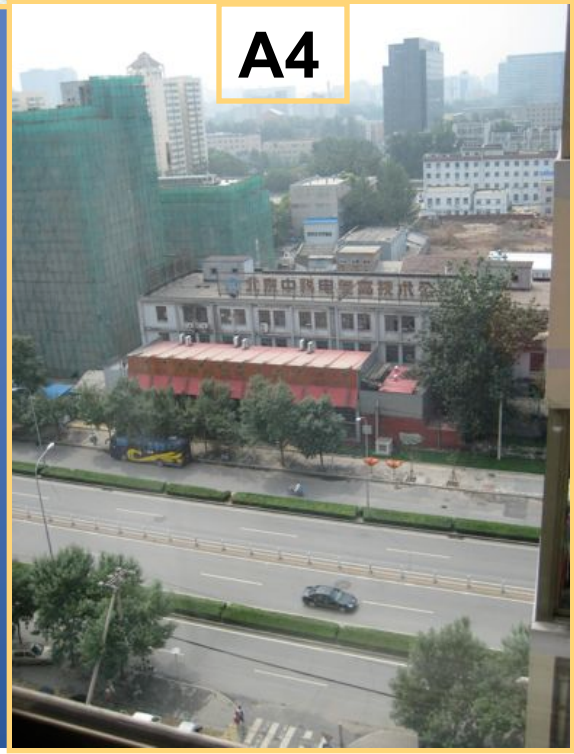
A3
- 210 m^3
- ~70 m from major roadway
- 16^{th} floor
- 2 adults

A4
- 220 m^3
- ~20 m from major roadway
- 14^{th} floor
- 5 adults + 1 adolescent

A1

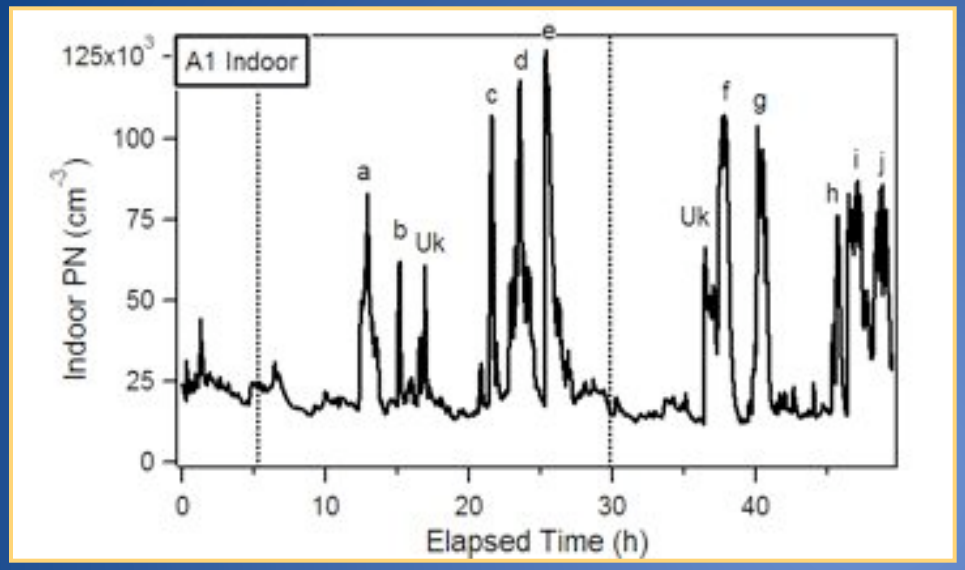
A2

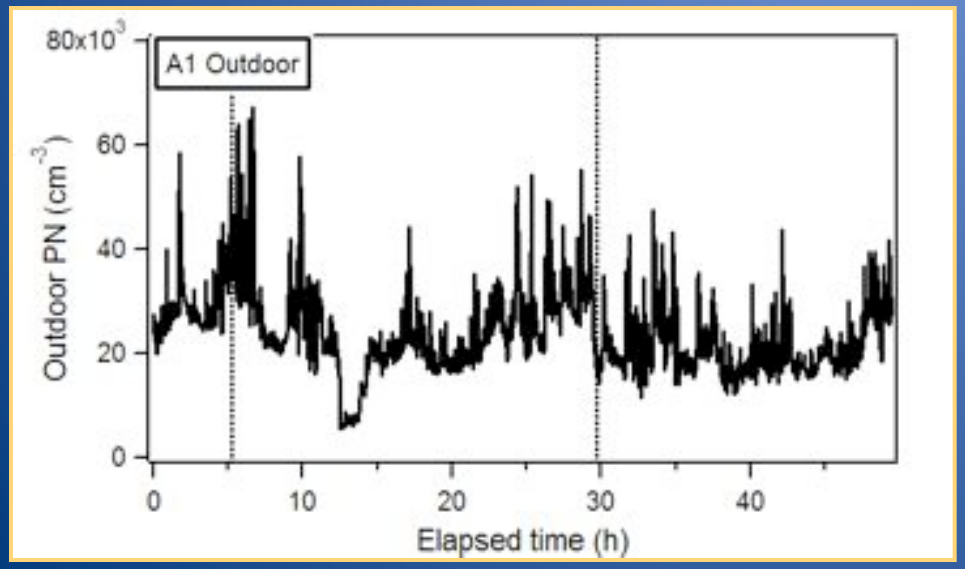

A3


A4

Field Set-up

Results: Apartment 1



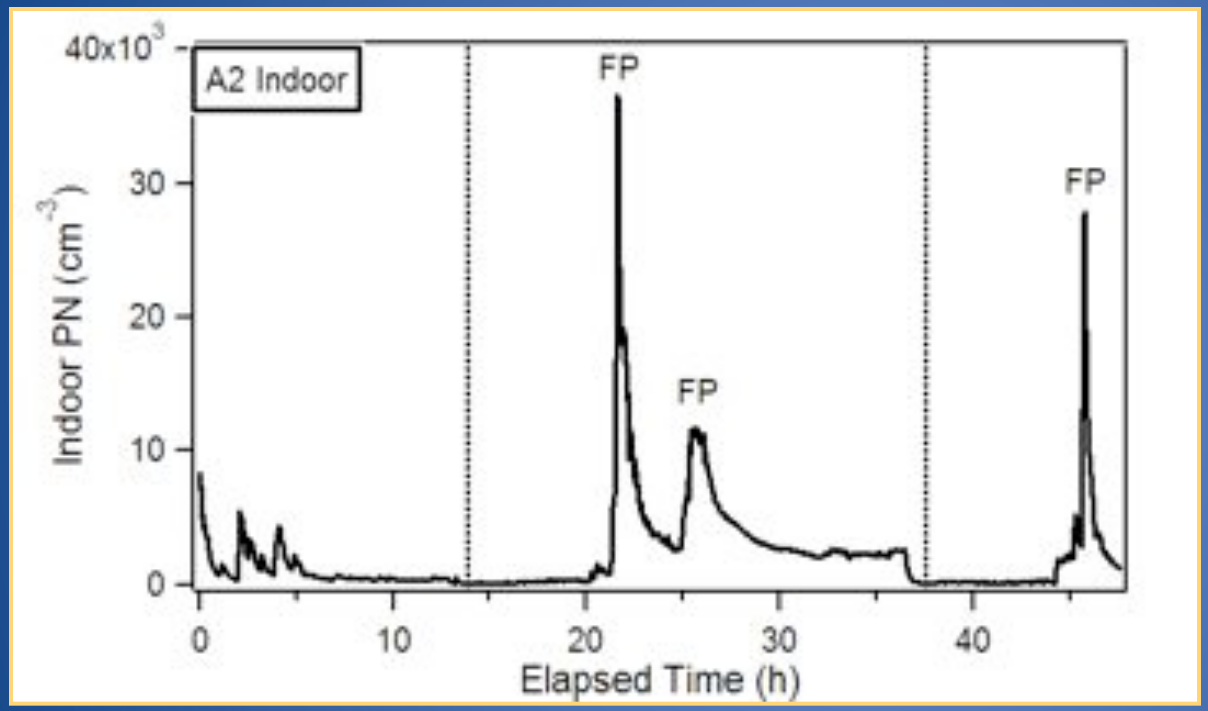


Awake (15 hrs):
PN in: 40,000 cm^{-3}
PN out: 24,000 cm^{-3}

Asleep (19 hrs):
PN in: 24,000 cm^{-3}
PN out: 27,000 cm^{-3}

Peak ID
a-f, h-i: Unknown
g: Fried eggs, bacon; toast
j: Fried beef, vegetables; toast

Results: Apartment 2

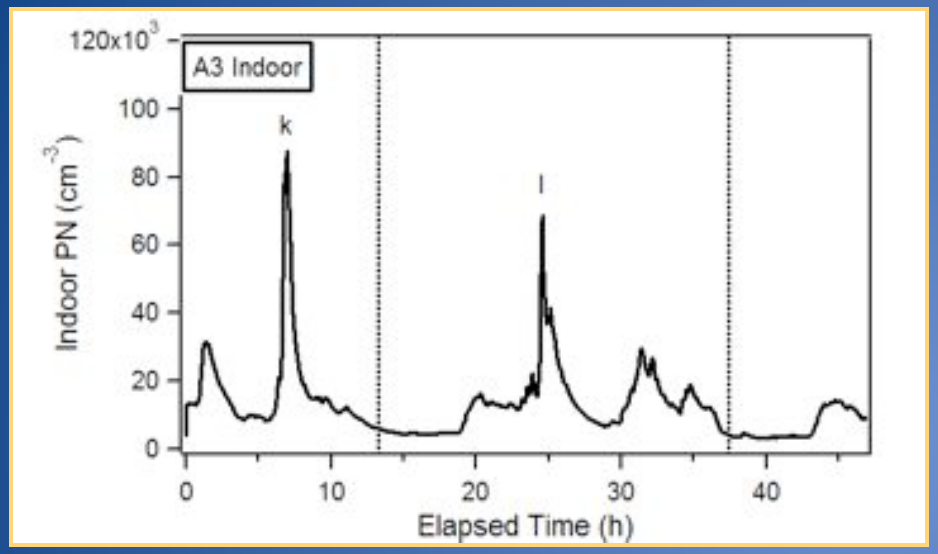


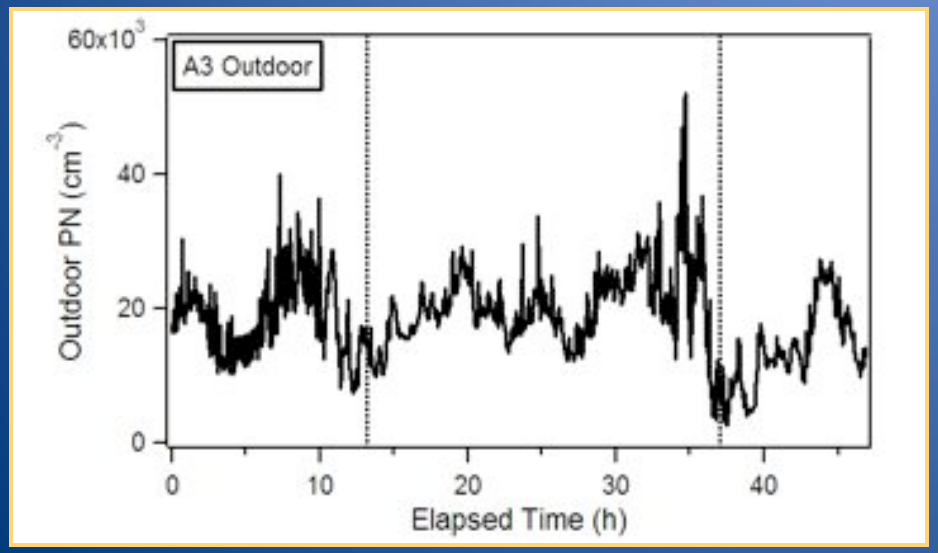
Awake (14 hrs):
PN in: 5,400 cm^{-3}

Asleep (14 hrs):
PN in: 300 cm^{-3}

Peak ID:
Pk 1: Toast
Pk 2: Noodles
Pk 3: Noodles and fried eggs

Results: Apartment 3





Awake (28 hrs):

PN in: 17,000 cm^{-3}

PN out: 21,000 cm^{-3}

Asleep (16 hrs):

PN in: 5,500 cm^{-3}

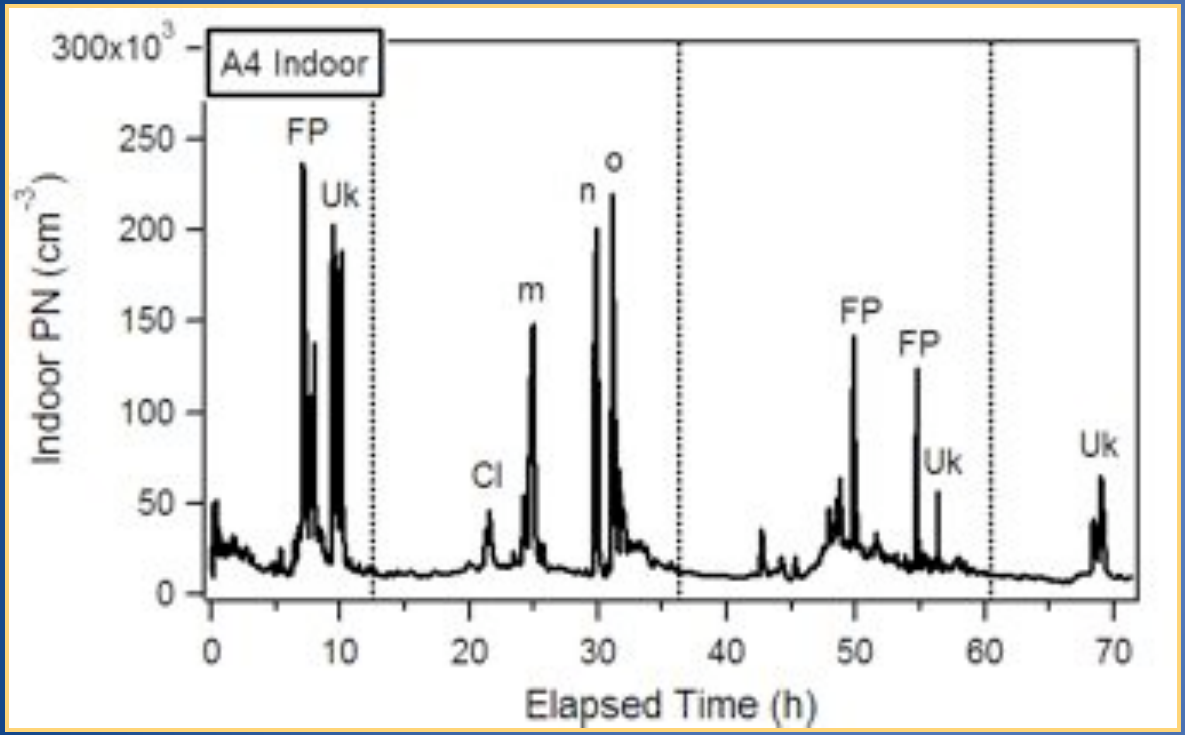
PN out: 14,000 cm^{-3}

Peak ID:

k: Fried eggs

l: Cooked porridge

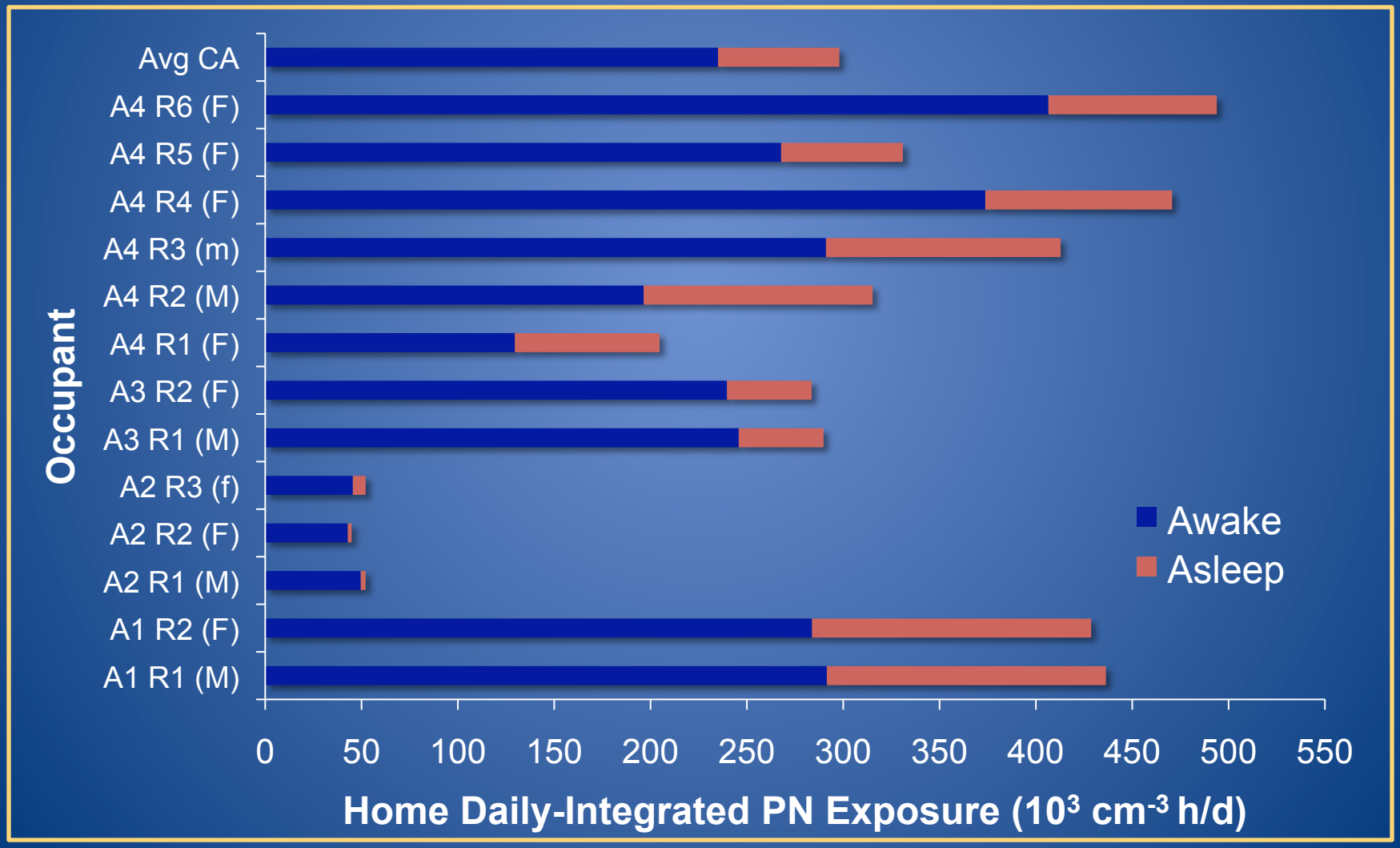
Results: Apartment 4



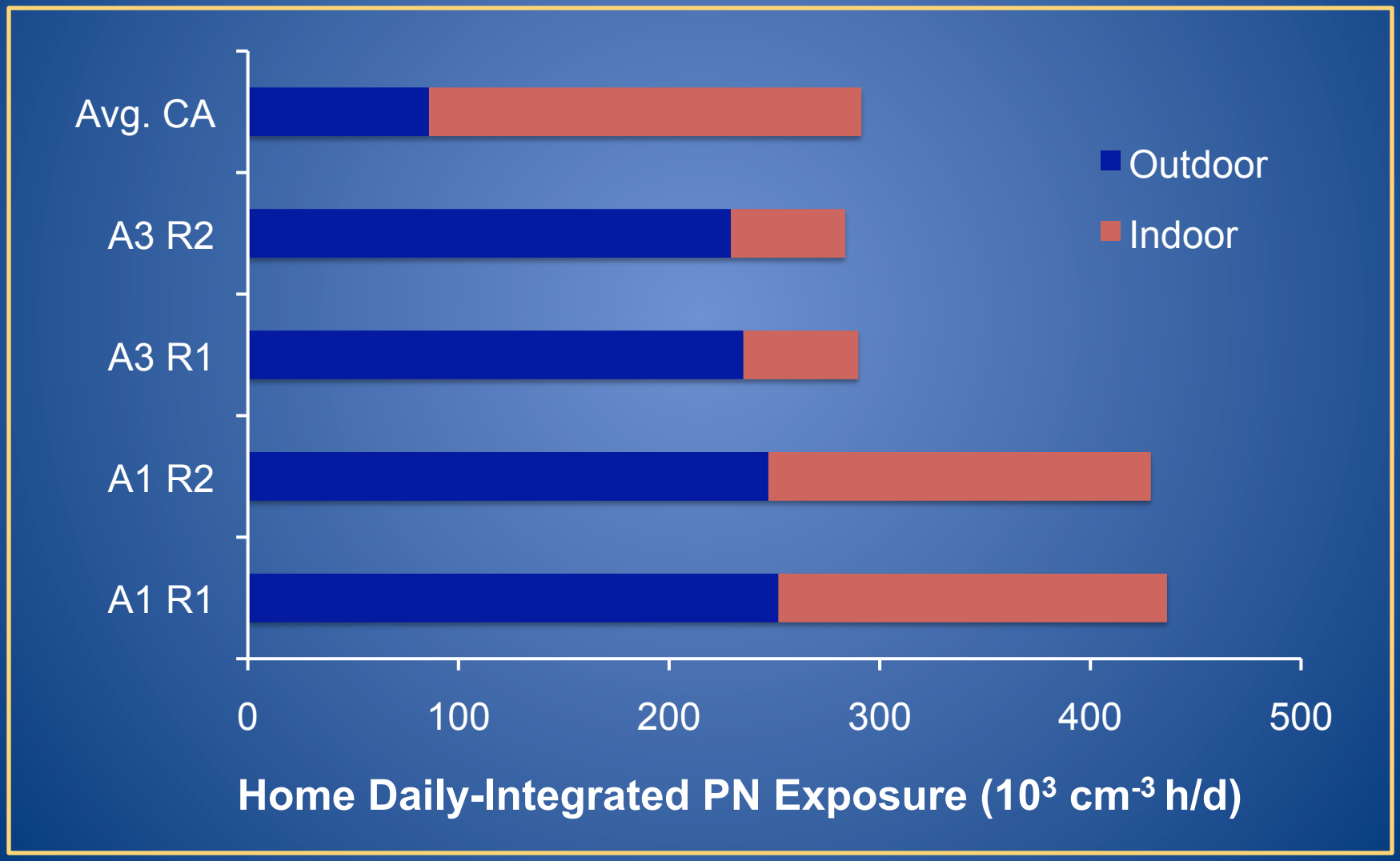
Awake (27 hrs):
PN in: 25,000 cm^{-3}

Asleep (22 hrs):
PN in: 11,000 cm^{-3}

Daily-Integrated PN Exposure



Exposure Apportionment: Indoor and Outdoor Sources



Summary: UFP exposure in Beijing high-rise apartments

- Apts. with greater natural ventilation:
  - Have faster decay of indoor generated peaks
  - Have higher proportion of outdoor particles
- Apartments with more indoor peak events had higher average exposure
- Comparable daily-integrated PN exposure in Beijing apartments and Bay Area homes

Thank you!

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Questions?

Berkeley
University of California

清華大學
Tsinghua University